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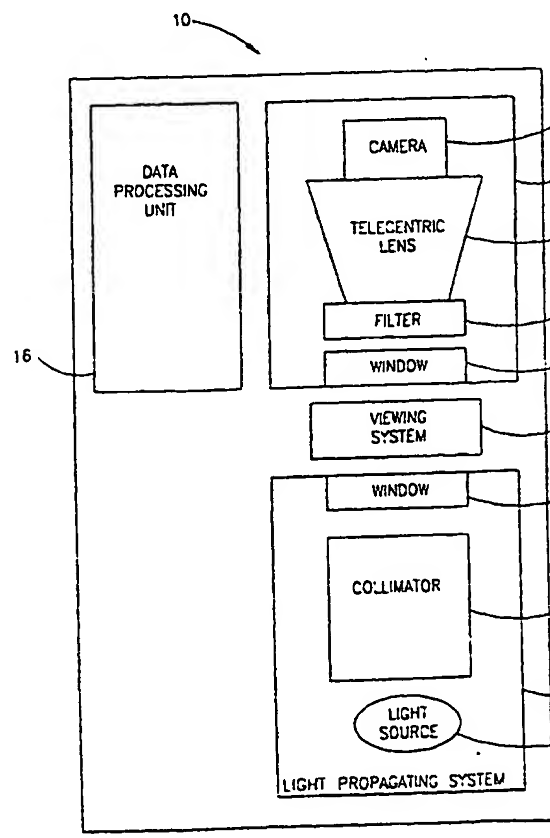
(54) Title: SHADOW CASTING METHOD FOR PROFILE MEASUREMENT

(57) Abstract

Apparatus (10) and method for determining critical dimensions of an object, using a light source (20) for propagating a non-coherent beam of light, which is collimated and propagated through a telecentric lens (30) towards a two-dimensional imaging device (32) for imaging the collimated beam of light. A viewing stand (40) situated between the collimator (22) and the telecentric lens (30), holds the object within the collimated beam of light, so that a silhouette of the object is obtained on the imaging device. A data processing means (16) coupled to the two-dimensional imaging device (32) for determining the critical dimensions of the object on the basis of its silhouette. An alignment unit (42, 44, 46, 50) is provided for aligning the object on the viewing stand, so that the silhouette of the object is nominally normal to the axis of the beam of light within a predetermined allowable tilt angle.



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SHADOW CASTING METHOD FOR PROFILE MEASUREMENT

FIELD OF THE INVENTION

The present invention provides a novel method and apparatus for automatically and accurately ascertaining specific dimensions of small objects such as bolts, screws, pistons and flywheels.

BACKGROUND OF THE INVENTION

Manufacturers of high-precision small parts, such as screws, bolts, pistons and fly wheels, for use in the electronics, aerospace and like industries, require means for accurate quality control of the small parts they manufacture, so as to ensure that the parts have been manufactured within the very fine tolerances dictated by the needs of their clients. Ideally, such means should be fully compatible with the manufacturing process itself, should provide a highly accurate measurement of each and every part that is manufactured – and not just a sample randomly chosen from any production batch – and should provide the required data in real time, i.e. as fast or faster than that of the production of the part itself (for a small part such as a screw, this may be as fast as one second per screw). Such a system must also be exceedingly accurate – to a level of accuracy that exceeds that of the specification of the small part itself – and it must also be cost effective, relative to the costs of manufacture of the small parts.

It has already been suggested to effectuate such a quality control system by measuring the part indirectly by means of its silhouette. However, the methods and apparatus that have been proposed for implementing such a system are fraught with numerous problems. Many of these stem from the fact that the silhouette which is to form the basis of the measurements must be an accurate silhouette of the object; otherwise, the measurements will not be sufficiently precise so as to be worthwhile. However, for various optical, mechanical and electronic reasons, it is very difficult to obtain an accurate silhouette of most objects. The type of light source used, the position of the object with respect to the imaging device on which the silhouette falls, the angular orientation of the object with respect to the beam of light and other electro-optical limitations – all of these affect the type of silhouette obtained, the accuracy of the silhouette, and the sharpness of the edges or contour of the silhouette. As a consequence, they also affect the degree of accuracy that can be obtained in measuring the object based upon the silhouette. Each of the techniques that have been proposed in the prior art attempt to deal with these problems somewhat differently; but none of the known techniques provides a comprehensive solution.

US Patent 5,150,623 (to Boeing) describes a video imaging system for sequentially measuring the dimensions of small objects, such as fasteners. The system includes a mechanical system for moving each fastener, one at a time, into the field of view of a pair of orthogonally-oriented cameras. A pair of orthogonally–oriented back-lights, each made up of an array of LEDs, and one each being directly opposite the field of view of one of the cameras, silhouettes each fastener and defines a camera image that is digitized for producing fastener dimensions. According to the description of this patent, this system does not require the precise mechanical positioning of the fastener, so as to obtain a correct definition of the plane of measurement of the silhouette. Rather, the orthogonal relationship of the cameras is utilized to calculate the position of the fastener relative to each camera, and the focus of each camera is adjusted until a

focus-adjusting algorithm determines that the focus of the fastener's edge is maximized. The arrangement proposed by Boeing does not require use of a collimated beam of light but, as noted, requires use of two cameras on to which a magnified image is focussed using suitable optics.

WO 97/21072 (Sherikon, Inc.) describes a system for measuring the silhouettes of bolts and other threaded fasteners, using a laser light source. The laser beam is focused by an object lens on a pinhole in a shade, providing a point source from which the beam diverges. A collimating lens produces a collimated broad beam of laser light dimensioned to encompass the fastener. The beam is incident on a planar two-dimensional detector array. No magnifying optics are employed, the detector being sufficiently large to achieve acceptable resolution. An image processor counts pixels between light/dark transitions to provide dimensional measurements that are compared to stored values to reach an accept/reject decision with regard to each fastener. The system in accordance with this application suffers from serious optical problems (a large amount of diffraction, speckles), as well as safety problems, due to the fact that it requires the use of a laser as its light source. It also does not include any means for correcting the angular orientation of the fastener with respect to the axis of the laser beam. As a consequence, it does not enable the accurate measurement of the length of the fastener in the plane normal to the axis of the laser beam.

The Boeing device is expensive owing to the requirement for two cameras, whilst the Sherikon device is expensive owing to the need for a large area detector. Furthermore, in both cases any deviation from normality between the object and the light beam, results in forelengthening or foreshortening of the silhouette. thus introducing errors. It would clearly be desirable to provide an apparatus using only a single compact camera, and which is more tolerant of slight tilt of the object being measured with respect to the imaging beam.

SUMMARY OF THE INVENTION

The present invention provides a method and apparatus for automatic, highly accurate, real-time measurement of small objects that improves on the methods and apparatus known in the art. The apparatus of the present invention is highly compact, portable, and adaptable for use in many industrial applications. It is simpler and more cost efficient than known devices, and yet provides an accuracy at least as great if not greater than that obtainable when using known devices. The method and apparatus of the present invention may be efficiently utilized as part of a quality control program for the manufacturers of small parts, to sort out sub-quality parts as they come off the manufacturing line. The method and apparatus of the present invention may also be efficiently utilized as an analytical tool for the manufacturers of small parts. providing real-time feedback with regard to imperfections in the manufacturing process, enabling the manufacturer to adjust the process so as to minimize imperfections, obtaining thereby greater productivity and a higher proportion of quality products.

There is therefore provided, in accordance with a preferred embodiment of the present invention, a method for determining critical dimensions of an object, the method comprising:

(a) directing a collimated beam of light to a two-dimensional digital imaging device;

(b) obtaining a silhouette of the object on the imaging device, by positioning the object within the beam of light;

(c) identifying a contour of the silhouette on the imaging device at a sub-pixel level of identification;

(d) identifying sets of critical points along the contour of the silhouette, defining thereby measurable geometric entities: and

(e) determining the critical dimensions of the object based upon the measurable geometric entities;

characterized in that:

(f) a plane of the object creating the silhouette is nominally normal to the beam of light within a predetermined allowable tilt angle.

In accordance with a preferred embodiment of the invention, the correct positioning of the object is attained by placing the object on a viewing stand which is tiltable along an axis normal to the axis of the beam, and adjusting the tilt of the viewing stand until the silhouette of the object is normal to the axis of the beam. Alternatively, slight tilt of the viewing stand may be tolerated and compensated for by means of software.

There is also provided, in accordance with a preferred embodiment of the present invention, an apparatus for determining critical dimensions of an object, the apparatus comprising:

a light source for propagating a beam of light;

a collimator for collimating the beam of light;

a two-dimensional imaging device for imaging the collimated beam of light;

a magnifying optics situated between the collimator and the imaging device;

a viewing stand situated between the collimator and the magnifying optics, adapted to hold the object within the collimated beam of light, so that a magnified silhouette of the object is obtained on the imaging device; and

a data processing means coupled to the two-dimensional imaging device for determining the critical dimensions of the object on the basis of its silhouette;

characterized in that:

an alignment unit is provided for aligning the object on the viewing stand, so that the silhouette of the object is nominally normal to the axis of the beam of light within a predetermined allowable tilt angle.

In accordance with a preferred embodiment of the invention, the alignment unit comprises a "swim table" tiltable along an axis perpendicular to the axis of the beam of light and a platform disposed on top of the swim table, the platform

comprising an elevated central portion and two relatively inferior outwardly extending fins defining two mutually displaced parallel edges on opposite sides of the central portion which appear to be of unequal heights when the platform is not horizontal.

Further, in accordance with a preferred embodiment of the invention, the imaging device comprises a "frame-transfer" CCD array camera or an "interline–transfer" CCD array camera.

The present invention also encompasses a method for correcting in real–time errors in production parameters, for use in conjunction with a system for manufacturing small objects, such as bolts, screws, pistons and flywheels, the method comprising:

(a) directing a collimated beam of light to a two-dimensional digital imaging device;

(b) obtaining a silhouette of an object on the imaging device, by positioning the object within the beam of light;

(c) identifying a contour of the silhouette on the imaging device at a sub-pixel level of identification;

(d) identifying sets of critical points along the contour of the silhouette, defining thereby measurable geometric entities; and

(e) determining the critical dimensions of the object based upon the measurable geometric entities;

characterized by:

(f) disposing a plane of the object creating the silhouette in a direction that is nominally normal to the beam of light within a predetermined allowable tilt angle;

(g) repeating steps **(b)** to **(e)** in respect of further objects;

(h) statistically evaluating the critical dimensions determined in step (e) for each of said objects: and

(i) adjusting production parameters based upon the statistical evaluation in step **(h)**.

There is also provided, in accordance with a preferred embodiment of the present invention, for use in a system for measuring critical dimensions of small objects by means of their silhouettes, a viewing platform comprising an elevated central portion capable of supporting the object and two relatively inferior fins on opposite sides of the central portion defining two mutually displaced parallel edges. In accordance with a preferred embodiment of the present invention, the viewing platform is mounted on a "swim table" which allows for tilting the platform along a given axis, within a predetermined allowable tilt angle.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention, as summarized above, will be more fully appreciated upon consideration of the following detailed description taken in conjunction with the attached drawings, wherein:

FIG. 1 provides a schematic overview of the basic components of apparatus for measuring the dimensions of objects in accordance with one embodiment of the present invention;

FIG. 2 provides a schematic representation of one of the sub-components of the apparatus of FIG. 1;

FIG. 3 provides a more detailed representation of a central component of the apparatus of FIG. 2;

FIG. 4 provides a schematic representation of an edge of a silhouette of an object whose critical dimensions may be determined in accordance with the present invention;

FIG. 5 is a pictorial representation of a micrometer or caliper simulation using the principles of the invention; and

FIG. 6 is a flow chart showing the principal operations associated with implementation of the micrometer or caliper simulation shown in Fig. 5.

DETAILED DESCRIPTION OF THE INVENTION

Reference is now made to FIG. 1, which presents a schematic overview of the basic components of the apparatus for measuring the dimensions of objects, in accordance with one embodiment of the present invention. The apparatus, referenced generally 10, comprises four main sub-components – a light propagation system 12, an imaging system 14, an object viewing system 18, and a data processing system 16, which may be constituted by a suitably programmed computer. In view of the fact that the apparatus is designed to operate in an industrial environment, in physical proximity to the machines which are used for manufacturing the objects whose dimensions are to be measured, the apparatus as a whole and all sub-components are preferably enclosed in suitable sealed enclosures (as shown schematically on FIG. 1) so as to prevent the entry of dust, oil and other debris that may cause damage to the apparatus and so as to minimize the entry of ambient light which may interfere with the imaging system.

Light propagating system 12 comprises a non-coherent light source 20, which preferably propagates monochromatic light. Light source 20 may be a single light emitting diode (LED), an array of LEDs, or a multi-mode laser attached to an optical fiber which produces monochromatic non-coherent light. In view of the fact that the ambient light of most industrial environments does not include light in the near infra-red band of the spectrum, it is advantageous to use a light source which produces light specifically in the near infra-red band of the spectrum. Situated in front of light source 20 are one or more light modifying devices, referenced generally 22 and constituting a collimator, whose goal is to modify the quality of the light propagated by light source 20 such that an intense, smooth, collimated beam of light will be obtained. Such devices may include a diffuser (preferably a holographic diffuser) for smoothing the profile of the light emitted by light source 20; an iris for concentrating the beam of light, and a lens (such as an achromatic doublet lens) for minimizing chromatic and other

aberrations and for collimating the beam of light which is directed therethrough. A protective window 24 which is affixed in a wall of the enclosure of light propagating system 12 enables the beam of light propagated by light source 20 to exit the enclosure of light propagating system 12 in the direction of imaging system 14.

As shown in FIG. 1, imaging system 14 is also contained within a suitable enclosure, such that the beam of light propagated by light propagating system 12 enters therein by means of a suitable window 26 which is affixed in a wall of the enclosure. Downstream of window 26 is a light filter 28, which is operative to filter out any ambient or other light, other than the collimated beam of light propagated by light propagating system 12. Further downstream is a high quality telecentric lens 30 (constituting a magnifying optics). such as that manufactured by Zeiss (Visionmess) or by Jenoptik. Telecentric lens 30 comprises a series of lenses (not shown) which block the entry of any ambient or stray light from the sides and which are adapted to only allow passage therethrough of light beams which are parallel to the optical axis. Use of a telecentric lens provides improved accuracy and allows for relatively free positioning of the object on the viewing stand, thereby reducing the cost of the positioning system. The magnification factor of the telecentric lens may be less than one, and therefore within the context of the specification and appended claims, the terms "magnifying optics" and "magnified" are not to be constrained to magnification by a factor greater than one. Downstream of telecentric lens 30 is a digital camera (constituting an imaging device) such as a video camera 32 which is operative to receive silhouette images of the objects placed within the beam of light propagated by light propagating system 12. Preferably, the video camera 32 comprises a two-dimensional array of charge coupled devices (CCDs) but in general may be any commercially available digital camera. According to a preferred embodiment, camera 32 is a "frame-transfer" type of video camera or an "interline transfer (Hyper HAD sensor)" type of video camera. such as that manufactured by Kodak

(Megaplus 1.4 model) or by Sony (XC-75 model). These provide a better solution to the "fill-factor" problem of CCD arrays. and make it possible to improve the modulation transfer function of the camera and to obtain more information about higher frequencies.

As can be seen from FIG. 1, object viewing system 18 is located between light propagating system 12 and imaging system 14. Its function is to provide a platform or base for each object whose dimensions are to be calculated, and to provide a means for assuring that the object is positioned properly with respect to the camera and the axis of the light beam. such that the silhouette of the object will be as accurate as possible. Preferably, object viewing system has a removable cover (not shown) which when in place functions as a filter with respect to the ambient light. The apparatus which may be used for placing objects on or within object viewing system 18 is not part of the present invention and is not described herein. However, it is appreciated that various apparatus can be utilized, including manual placement, placement by means of automated electronic devices, such as a robot, or placement by means of mechanical devices, such as a tube positioned vertically above the viewing system which allows each object in turn to fall down by gravity to an appropriate location within the viewing system.

The specific structure of object viewing system 18 may be more fully appreciated with reference to FIG. 2 and FIG. 3. As can be seen from FIG. 2, object viewing system 18 comprises a "swim table" type of stand 40, having a base 42 and a surface plate 44 resting thereon. Attached to the base plate 40 is a motor 46 that is operative to selectively control the raising or lowering of one edge of surface plate 44 by means of a screw 48. It will be appreciated that the raising or lowering of the edge of surface plate 44 affects the tilt angle of surface plate 44 with respect to the base, and as a consequence. also affects the tilt angle of any object resting on top of surface plate 44. Stand 40 constitutes an alignment unit and is positioned such that the surface plate 44 may be tilted along an axis

perpendicular to the axis of the light beam propagated by light propagating system 12 and directed to imaging system 14. Stand 40 may be any type of "swim table" that is commercially available (such as that manufactured by Newport). However, the sensitivity of height adjustment of the "swim table" preferably is in the range of ±12.5 microns (0.017°).

Resting securely on top of surface plate 44, or inserted within surface plate 44, is a viewing platform 50, whose features can be more fully appreciated with reference to FIG. 3. Viewing platform 50 comprises a base portion 52, which is adapted to secure the platform to surface plate 44 (FIG. 2), and a raised central portion 54 on which the object to be measured sits. Extending away in opposite directions from central portion 54, at a height different from the height of central portion 54, are two flanges or fins 56 and 58. Fins 56 and 58 have sharply defined and carefully honed upper edges which define two hypothetical lines extending across viewing platform 50 that are parallel to each other and at a fixed distance from one another.

When the apparatus of the present invention is in operation, the upper portions of viewing platform 50 interpose the beam of light propagated by light propagating system 12 such that silhouettes of the edges of fins 56 and 58 are projected on camera 30 of imaging system 14. The geometry of fins 56 and 58 is such that the relative alignment of the silhouettes of these edges provides an accurate indicator of the degree of tilt of the viewing stand with respect to the axis of the beam of light. Thus, if the heights of the edges are not fully aligned, this indicates that the silhouette of any object resting on top of the viewing stand is not normal to the axis of the beam of light; as a consequence, the silhouette will be varied in height and will not provide a basis for the accurate measurement of the height of the object, unless such variation is compensated for. By adjusting the tilt of plate 44, full alignment of the silhouettes of the edges of fins 56 and 58 can be obtained, thereby assuring that the silhouette of the object resting on top of the viewing stand is normal to the axis of the beam of light. It is to be noted that

mechanical limitations of the swim table may not allow full or true alignment of fins 56 and 58. However, this drawback can be overcome analytically, based upon the geometry of viewing platform 50, since the height difference between the upper edges of the silhouette of fins 46 and 48. when divided by the fixed distance between the hypothetical line defined by fins 46 and 48, gives the tangent of the tilt angle.

The object whose dimensions are to be measured in accordance with the present invention may be placed anywhere on central portion 54 of viewing platform 48, and there is no need to adjust its position thereon in any direction. The only adjustment that must be done is the adjustment of the tilt angle of the viewing platform, as described above, so that the silhouette of the object will be normal to the axis of the beam of light. The use of a telecentric lens, and a camera having a CCD array of sufficient linear dimensions. ensures that a full and accurate silhouette of the object will be obtained. once the object has been positioned anywhere on central portion 54 of viewing platform 50 and the tilt angle of the viewing platform has been adjusted in the manner described above.

Data processing system 16 comprises a microprocessor, such as a Pentium II, and associated hardware and software. (Pentium is a Registered Trademark of Intel Corporation.) Data processing system 16 receives from camera 32 a digital image of the silhouette of the object which has been placed on object viewing system 18, determines the critical dimensions of the object, and provides appropriate output signals to external devices (not shown), such as a video screen for display to an operator, or to a sorting device which is operative to remove the objects from viewing stand 18 and sort them into groups. such as those that have met quality control dimensions and those that have not. Data processing system 16 may also provide analytical (including statistical) information with regard to the objects whose critical dimensions have been determined, and this information can then be utilized to adjust various parameters of the production process to achieve greater efficiency and productivity.

Reference is now made to FIG. 4 which illustrates a silhouette of a small object whose dimensions may be accurately determined utilizing the apparatus and method of the present invention. It will be appreciated that the silhouette shown schematically in FIG. 4 is not identical to the actual silhouette that is obtained on the video camera utilizing the apparatus of the present invention. It is, in fact, an idealization of the actual silhouette. since the contour of the silhouette of FIG. 4 is cleanly and sharply defined, while in reality the contour of the silhouette that is projected on the video camera is relatively fuzzy, with the degree of fuzziness a function of the pixel size of the camera (and distortions inherent in the optical system). However, even if video cameras of very high resolution are used, having a projected pixel size of approximately 40 microns, significant fuzziness remains, so that measurements carried out on the level of pixels alone cannot provide data to a significant level of accuracy. This limitation inherent in the use of silhouettes is overcome by image-processing using software which analyzes the data obtained on the pixel level and translates it to highly accurate data on the sub-pixel level. By such means, the present invention provides measurements that are accurate at a level of accuracy on the order of 1 micron. The image-processing software is not itself a feature of the invention and may be based on algorithms available either commercially or in the public domain. to which reference is made below.

The method of the present invention is based. in part, on a prior analysis of the idealized contour of an object, such as that shown in FIG. 4, which parses the contour into a series of "primitives", each of which defines a basic geometric entity. Thus, the contour of the object illustrated in FIG. 4, when properly parsed, is defined as a combination of an oblong *abcd* [the silhouette of a cylinder], a trapezoid *cbef* [the silhouette of a cone]. a partial cylinder *efgh* [with edges *eh* and *fg* representing the partial radius of a circle], and an oblong *ghij*. It will be seen that each "primitive" is defined by at least three specific points. each of which marks an actual change in direction of the contour of the object. This basic

information is then utilized by the image-processing software for the sub-pixel analysis of the silhouette of the object.

The method utilized by Applicant, within the framework of the present invention, involves the following basic steps:

(a) obtaining the contour line of the silhouette. by separating the silhouette from the background, using image-processing software based upon the Canny algorithm which is incorporated herein by reference (J. F. Canny, "*A Computational Approach to Edge Detection*," IEEE Trans. On Pattern Analysis and Machine Intelligence, Vol. 8, No. 6, Nov. 1986, pp. 679-698);

(b) locating a series of critical points, along the contour line of the silhouette, based upon changes in contour parameters. using image-processing software based upon the Teh-Chin algorithm which is incorporated herein by reference (Cho-Huak Teh and Roland T. Chin, "*On the Detection of Dominant Points on Digital Curves*," IEEE Trans. On Pattern Analysis and Machine Intelligence, Vol. 11, No. 8, Aug. 1989, pp. 859-872):

(c) identifying the "primitives" based upon sets of critical points; and

(d) calculating the dimensions of the primitives.

Based upon the calculated dimensions of the primitives, various critical dimensions of the object as a whole can then be determined. These may be any critical dimensions which are of interest to the manufacturer of the object, and not necessarily the dimensions of the primitives themselves. For example, the method of the present invention will provide an accurate measurement of the overall length, *A*, of the object (FIG. 4), or the distance *B* defined as the distance between the top edge of the object and the mid point of the head.

So far there has been described the manner in which the data processing system 16 image processes the pixel data associated with the object silhouette in order to compute critical dimensions of the object. The data processing system 16 may also be programmed to simulate use of a micrometer or caliper for

measuring differential dimensions of the object, such as the effective diameter of a bolt at various points along the shank thereof.

Figs. 5 and 6 show pictorially a simulated micrometer or caliper 60 and a flow chart detailing a method for use thereof to measure the diameter of an object silhouette 61. It will be noted that the object silhouette 61 has a pair of irregular edges 62 and 63 such that the distance between the edges varies along the length of the object silhouette. The micrometer 60 has a pair of opposing, adjustable blades shown schematically as 64 and 65 which may be adjusted until they touch the respective edges 61 and 62 at those points between which the diameter is to be measured. The blades 64 and 65 may themselves have an adjustable profile, for example, round or beveled and may also have a selectable diameter or width. The dimension of the micrometer blades defines the maximum number of discrete non-overlapping measurements that can be made along the length of the object silhouette. The number of discrete measurements is selected by the operator and the data processing system 16 checks that this is valid, i.e. that given the width or diameter of the micrometer blades set by the operator, the selected number of discrete non-overlapping measurements that can be made along the length of the object silhouette is no greater than the maximum possible.

Thereafter, starting away from a first side of the edges profile, e.g. displaced from the edge 61, the data processing system 16 constructs a pair of opposing parallel lines of length equal to that of the micrometer blades (as specified by the operator) and of sufficient spacing to straddle the edges 61 and 62. The inter-blade spacing is now progressively reduced until the blades 64 and 65 touch the respective edges 61 and 62. This is easily and quickly determined by the data processing system 16 based on the intersecting pixels of the edges and the micrometer blades. If necessary, the edges 61 and 62, being non-uniform in cross–section, may be tilted and the micrometer blades 64 and 65 drawn closer together, until the distance between the micrometer blades is minimized. The

distance between the micrometer blades 64 and 65 may now be computed based on the number of pixels between the opposing parallel lines.

The starting point of the micrometer blades 64 and 65 is now moved along the length of the object silhouette by the desired incremental distance set by the operator. If the micrometer blades are still within the limits of the object silhouette, further measurements may be taken in like manner.

It will be appreciated that since the system of measurement in accordance with the present invention is an optical system which utilizes a series of lenses, a certain amount of optical distortion will always be present. In order to correct for such distortions, the system as a whole must be calibrated, so as to obtain data that define the distortion parameters which can then be used to correct the raw data obtained each time the silhouette of an object is obtained for analysis. Such calibration preferably is done utilizing a dot matrix calibration mask, such as that manufactured by Zeiss, and measuring pins such as manufactured by Mitutoyo on the basis of which a set of functions can be constructed for correcting inaccuracies arising from optical distortions. The same mask may also be used for correlating the data obtained on the pixel level with the actual metrics in the plane of measurement.

As has already been indicated, the present invention may be utilized not only within the framework of a quality control program for the manufacturer of small parts, but also as an analytical tool, providing real-time feedback to the manufacturer with regard to various production parameters (based in part on a statistical analysis of the dimensions of a pre-determined number of objects). Because the present invention provides accurate, critical information in real-time, it may be utilized not only after the conclusion of the full production process, but at each stage of the production process as well. The resultant advantages are many, including the weeding-out at an earlier stage of the production process of imperfect parts, a reduction in the amount of scrap, and a savings in machine time for the further production of imperfect parts. Thus, the present invention provides

additional benefits and advantages that are not available when utilizing the techniques of the prior art relating to the measurement of silhouettes.

As noted above, the data processing system may be a suitably programmed computer and, to this end, the software components may be provided in the form of a machine readable data carrier bearing program instructions for reading by the computer.

It will be appreciated that the present invention is not limited by the specific description provided herein, and encompasses other embodiments and variations which are readily appreciated by a man of the art. For example, whilst the use of a non-coherent light source results in more accurate measurements, the invention also contemplates the use of coherent light in those cases where some accuracy may be sacrificed. The present invention is only limited by the claims which follow:

CLAIMS:

1. A method for determining critical dimensions of an object, the method comprising:

(a) directing a collimated beam of light to a two-dimensional digital imaging device;

(b) obtaining a silhouette of the object on the imaging device, by positioning the object within the beam of light;

(c) identifying a contour of the silhouette on the imaging device at a sub-pixel level of identification;

(d) identifying sets of critical points along the contour of the silhouette, defining thereby measurable geometric entities; and

(e) determining the critical dimensions of the object based upon the measurable geometric entities;

characterized in that:

(f) a plane of the object creating the silhouette is nominally normal to the beam of light within a predetermined allowable tilt angle.

2. The method according claim 1, wherein step (f) comprises:

i) placing the object on a viewing stand which is tiltable along an axis normal to the axis of the beam within said predetermined allowable tilt angle, and

ii) adjusting the tilt of the viewing stand until the silhouette of the object is normal to the axis of the beam

3. The method according to Claim 2, wherein step (i) comprises:

(1) providing a platform comprising an elevated central portion for supporting the object and two relatively inferior outwardly extending fins defining two mutually displaced parallel edges on opposite sides of the central portion. and

(2) tilting the platform until the edges of said fins appear to be at equal heights.

4. The method according claim 1, wherein step (g) comprises:

i) measuring a tilt angle of the plane of the object relative to the beam of light, and

ii) compensating for said tilt angle when determining the critical dimensions of the object.

5. The method according to Claim 4, wherein step (i) comprises:

(1) providing a platform comprising an elevated central portion for supporting the object and two relatively inferior outwardly extending fins defining two mutually displaced parallel edges on opposite sides of the central portion, and

(2) measuring a height discrepancy between the edges of said fins in order to infer said tilt angle therefrom.

6. The method according to any one of the preceding claims, further including simulating measurement of a dimension of the object between two locations thereof by a micrometer having a pair of micrometer blades for contacting the silhouette of the object at said locations.

7. The method according to Claim 6, including the steps of:

(a) specifying a desired width of the micrometer blades,

(b) specifying a desired incremental distance along a length of the object silhouette between successive measurements.

(c) starting away from a first side of opposing edges of the object silhouette, constructing a pair of opposing parallel lines of length equal to that of the micrometer blades specified in (a) and of sufficient spacing to straddle the edges,

(d) progressively reducing the spacing between the blades until the blades touch the respective edges,

(e) if necessary, tilting the edges and drawing the micrometer blades closer together, until the distance between the micrometer blades is minimized, and

(f) computing the distance between the micrometer blades based on the number of pixels between the opposing parallel lines.

8. The method according to Claim 7, further including:

(g) moving the starting point of the micrometer blades along the length of the object silhouette by the desired incremental distance set in (a), and

(h) if the micrometer blades are still within the length of the object silhouette, taking further measurements by repeating steps (c) to (g).

9. The method according to any one of the preceding claims, wherein the beam of light is non-coherent.

10. A method for correcting in real–time errors in production parameters, for use in conjunction with a system for manufacturing small objects, such as bolts, screws, pistons and flywheels, the method comprising:

(a) directing a collimated beam of light to a two-dimensional digital imaging device;

(b) obtaining a silhouette of an object on the imaging device, by positioning the object within the beam of light;

(c) identifying a contour of the silhouette on the imaging device at a sub-pixel level of identification;

(d) identifying sets of critical points along the contour of the silhouette, defining thereby measurable geometric entities; and

(e) determining the critical dimensions of the object based upon the measurable geometric entities;

characterized by:

(f) disposing a plane of the object creating the silhouette in a direction that is nominally normal to the beam of light within a predetermined allowable tilt angle;

(g) repeating steps **(b)** to **(e)** in respect of further objects;

(h) statistically evaluating the critical dimensions determined in step **(e)** for each of said objects; and

(i) adjusting production parameters based upon the statistical evaluation in step **(h)**.

11. Apparatus (10) for determining critical dimensions of an object, comprising:

a light source (20) for propagating a beam of light:

a collimator (22) for collimating the beam of light:

a two-dimensional imaging device (32) for imaging the collimated beam of light;

a magnifying optics (30) situated between the collimator and the imaging device;

a viewing stand (40) situated between the collimator (22) and the magnifying optics (30), adapted to hold the object within the collimated beam of light, so that a magnified silhouette of the object is obtained on the imaging device; and

a data processing means (16) coupled to the two-dimensional imaging device (32) for determining the critical dimensions of the object on the basis of its silhouette;

characterized in that:

an alignment unit (42, 44, 46, 50) is provided for aligning the object on the viewing stand, so that the silhouette of the object is nominally normal to the axis of the beam of light within a predetermined allowable tilt angle.

12. Apparatus according to claim 11, wherein the alignment unit comprises a "swim table" (40) tiltable along an axis perpendicular to the axis of the beam of light.

13. Apparatus according to claim 11 or 12, wherein the viewing stand includes a platform (50) comprising an elevated central portion (54) capable of supporting the object and two relatively inferior outwardly extending fins (56. 58) defining two mutually displaced parallel edges on opposite sides of the central portion.

14. Apparatus according to any of claims 11 to 13, wherein the imaging device is a "frame-transfer" CCD array.

15. Apparatus according to any of claims 11 to 13, wherein the imaging device is an "interline-transfer" CCD array.

16. Apparatus according to any one of the Claims 11 to 15, being adapted to simulate measurement of a dimension of the object between two locations thereof by a micrometer (60) having a pair of micrometer blades (64, 65) for contacting the silhouette of the object at said locations.

17. Apparatus according to any of claims 11 to 16, wherein the beam of light is non-coherent.

18. Apparatus according to any of claims 11 to 17, wherein the magnifying optics is a telecentric lens.

19. A tiltable platform (50) comprising an elevated central portion (54) and two relatively inferior outwardly extending fins (56. 58) defining two mutually displaced parallel edges on opposite sides of the central portion which appear to be of unequal heights when the platform is not horizontal.

20. A computer program product comprising a computer usable medium having computer readable program code embodied therein for determining critical dimensions of a pixelized object silhouette, the computer readable program code in said computer program product comprising:

(a) computer readable program code for causing a computer to identify a contour of the silhouette on the imaging device at a sub-pixel level of identification;

(b) computer readable program code for causing a computer to identify sets of critical points along the contour of the silhouette, defining thereby measurable geometric entities; and

(c) computer readable program code for causing a computer to compute the critical dimensions of the object based upon the measurable geometric entities.

21. The computer program product according to Claim 20, wherein the computer readable program code in said computer program product further comprises:

(d) computer readable program code for causing a computer to compensate for non-orthogonality of the object relative to an imaging light beam when determining the critical dimensions of the object.

22. A program storage device readable by a machine, tangibly embodying a program of instructions executable by the machine to perform method steps for determining critical dimensions of a pixelized object silhouette, said method steps comprising:

(a) identifying a contour of the silhouette on the imaging device at a sub-pixel level of identification;

(b) identifying sets of critical points along the contour of the silhouette, defining thereby measurable geometric entities: and

(c) computing the critical dimensions of the object based upon the measurable geometric entities.

23. A program storage device readable by a machine, tangibly embodying a program of instructions executable by the machine to perform method steps for determining critical dimensions of a pixelized object silhouette, said method steps comprising:

(a) identifying a contour of the silhouette on the imaging device at a sub-pixel level of identification;

(b) identifying sets of critical points along the contour of the silhouette, defining thereby measurable geometric entities;

(c) computing the critical dimensions of the object based upon the measurable geometric entities; and

(d) compensating for non-orthogonality of the object relative to an imaging light beam when determining the critical dimensions of the object.

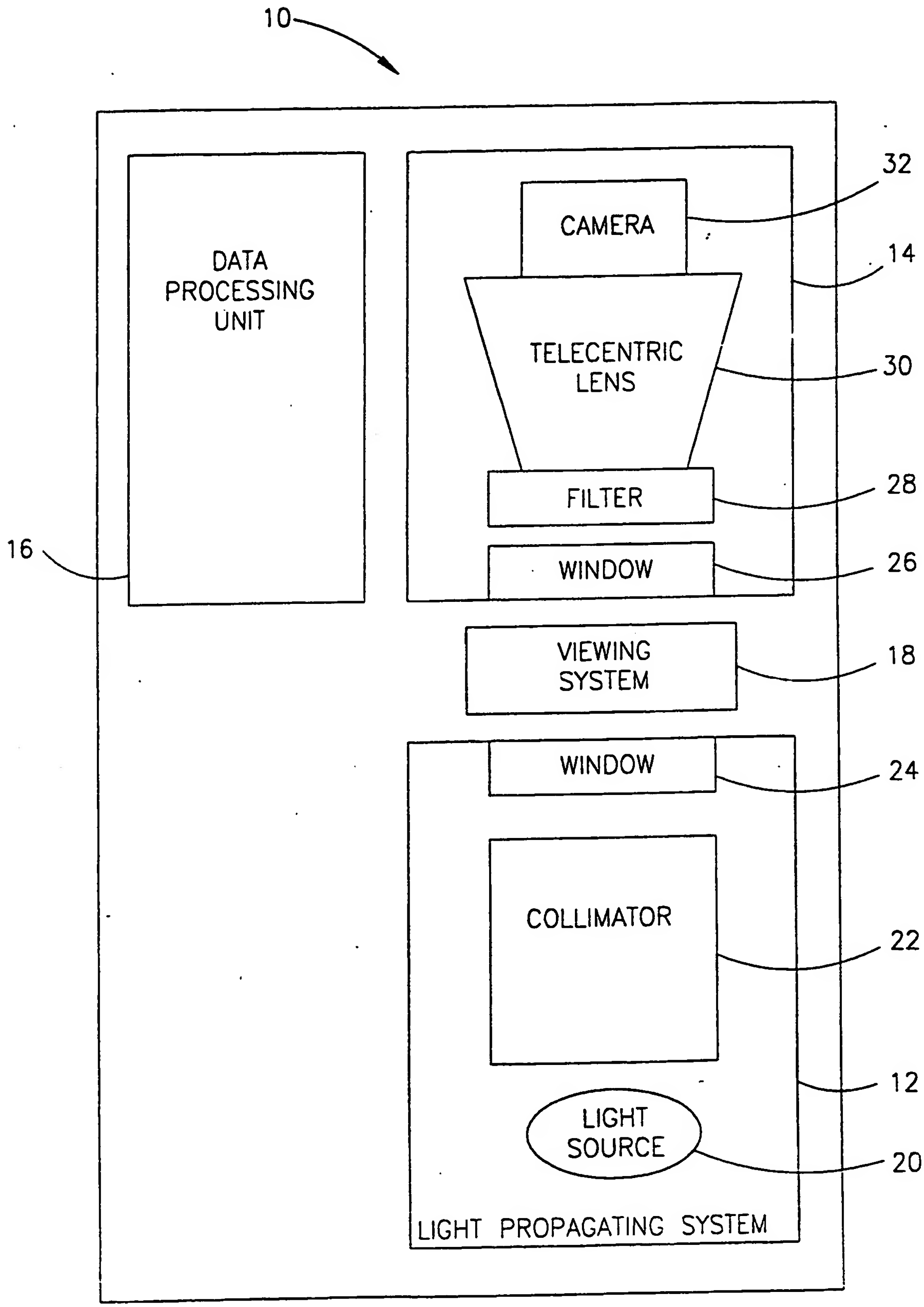
10
DATA PROCESSING UNIT
16
CAMERA
32
14
TELECENTRIC LENS
30
FILTER
28
WINDOW
26
VIEWING SYSTEM
18
WINDOW
24
COLLIMATOR
22
12
LIGHT SOURCE
20
LIGHT PROPAGATING SYSTEM

FIG.1

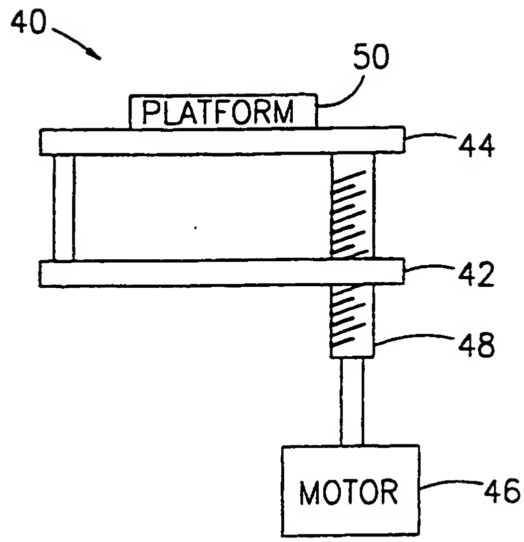

FIG.2

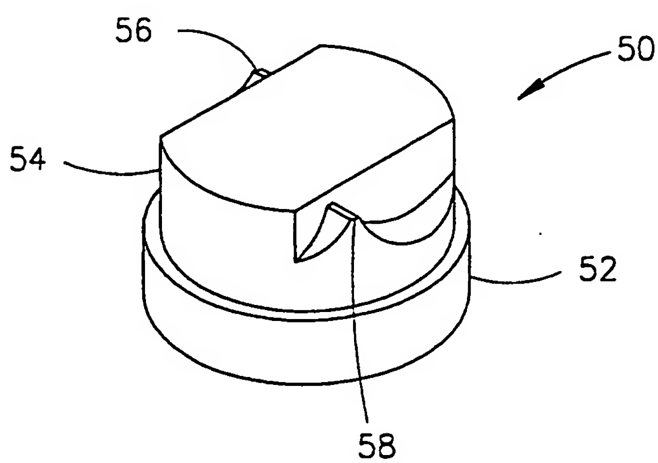

FIG.3

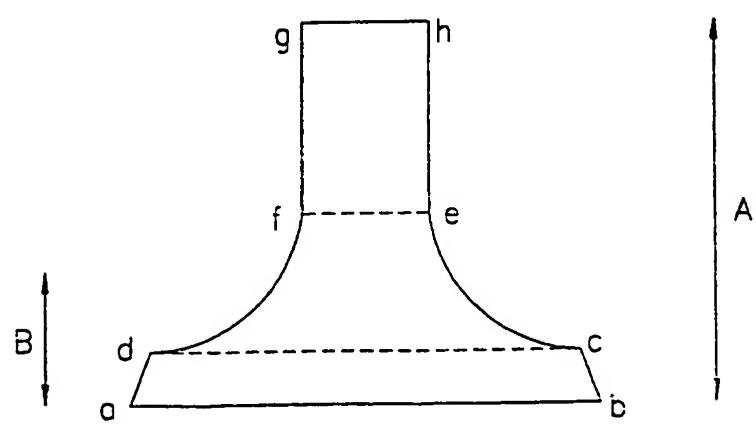

FIG.4

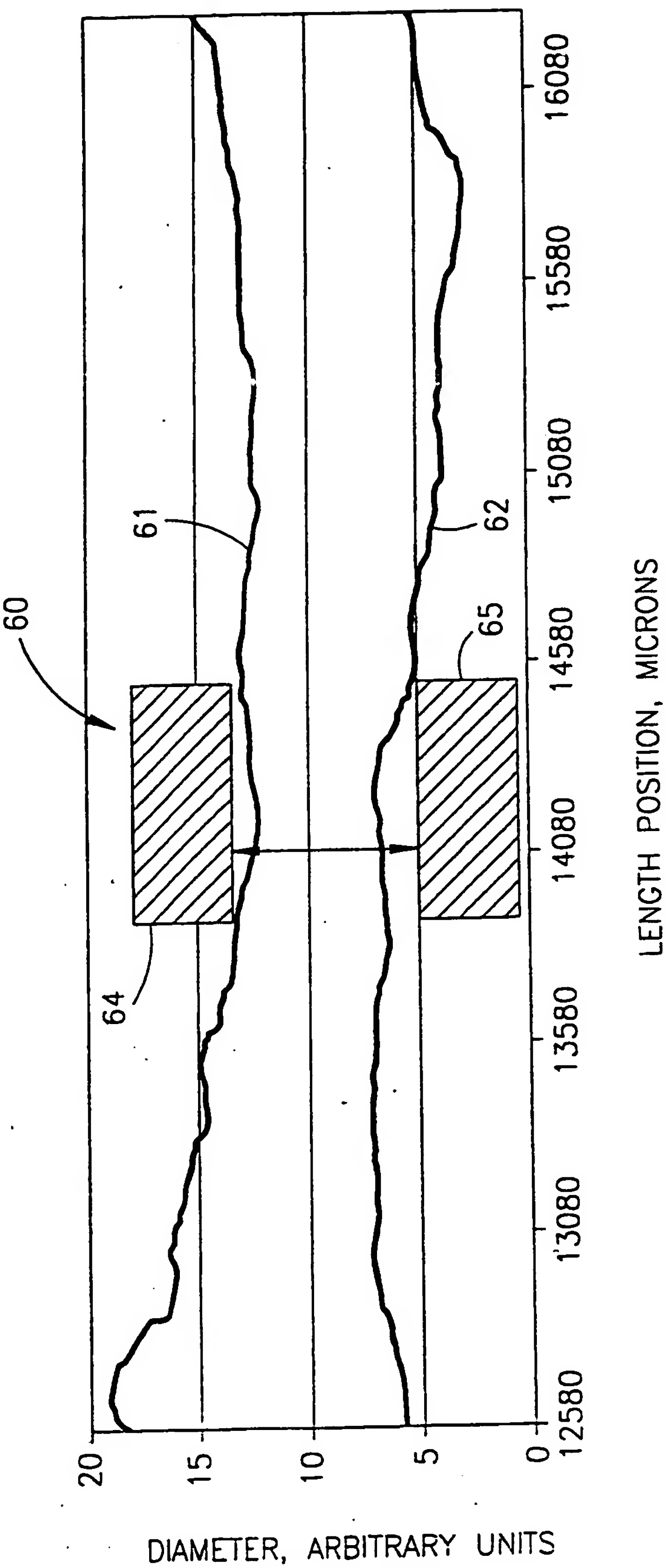
60
61
62
64
65
20
15
10
5
0
12580
13080
13580
14080
14580
15080
15580
16080
LENGTH POSITION, MICRONS
DIAMETER, ARBITRARY UNITS

FIG.5

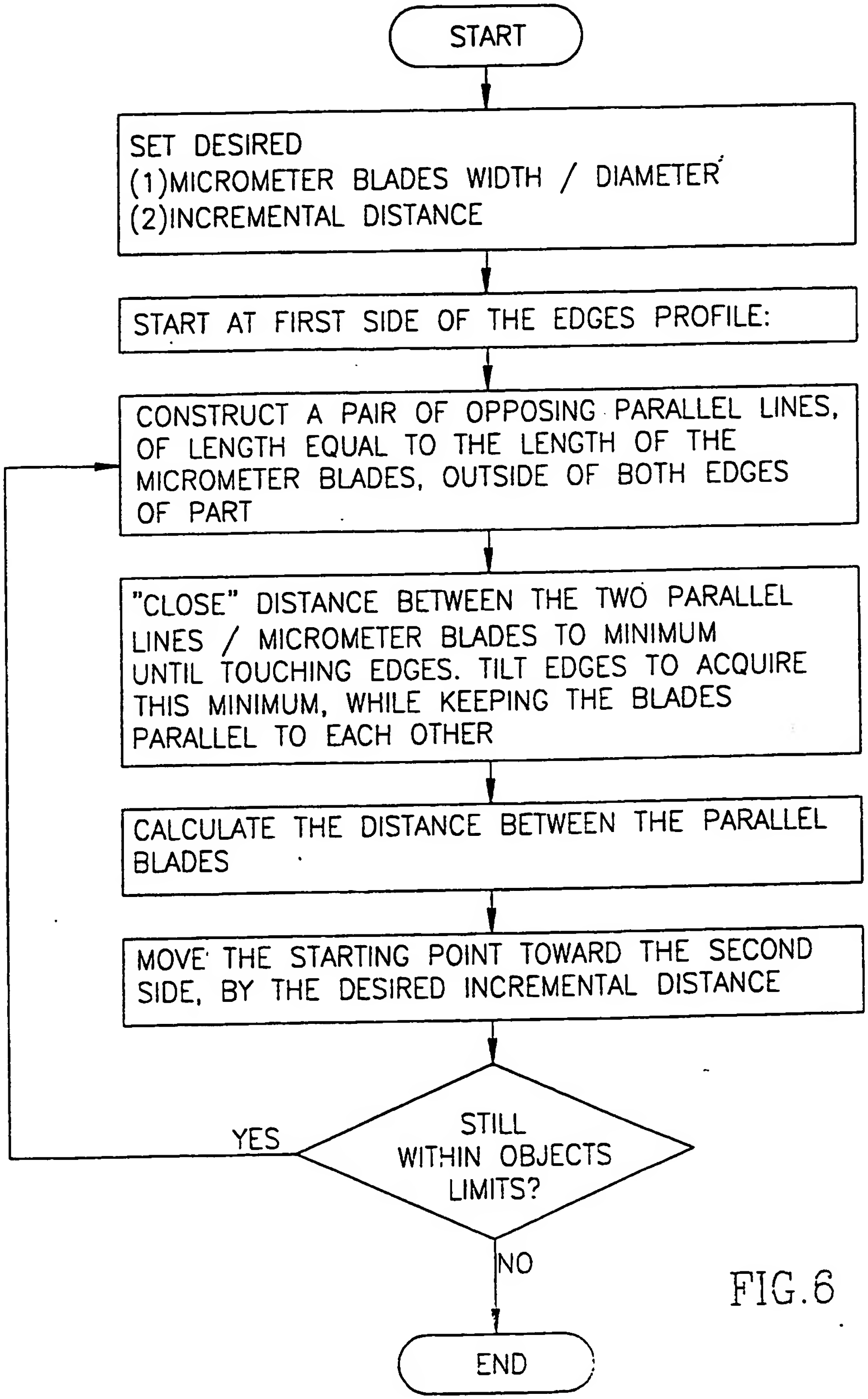
START
SET DESIRED
(1)MICROMETER BLADES WIDTH / DIAMETER
(2)INCREMENTAL DISTANCE
START AT FIRST SIDE OF THE EDGES PROFILE:
CONSTRUCT A PAIR OF OPPOSING PARALLEL LINES, OF LENGTH EQUAL TO THE LENGTH OF THE MICROMETER BLADES, OUTSIDE OF BOTH EDGES OF PART
"CLOSE" DISTANCE BETWEEN THE TWO PARALLEL LINES / MICROMETER BLADES TO MINIMUM UNTIL TOUCHING EDGES. TILT EDGES TO ACQUIRE THIS MINIMUM, WHILE KEEPING THE BLADES PARALLEL TO EACH OTHER
CALCULATE THE DISTANCE BETWEEN THE PARALLEL BLADES
MOVE THE STARTING POINT TOWARD THE SECOND SIDE, BY THE DESIRED INCREMENTAL DISTANCE
STILL WITHIN OBJECTS LIMITS?
YES
NO
END

FIG.6

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/IL 99/00364

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5150623 A	29-09-1992	NONE	
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EP 0679883 A	02-11-1995	AU 689547 B	02-04-1998
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US 5753905 A	19-05-1998	US 5610391 A	11-03-1997
		AU 695387 B	13-08-1998
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		JP 8184416 A	16-07-1996
		PL 310151 A	04-03-1996
		ZA 9507154 A	17-04-1996

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IL 99/00364

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01B11/24 G01B5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01B B21J B07C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 5 150 623 A (WOODS MARK A) 29 September 1992 (1992-09-29) cited in the application column 4, line 33 - line 50 column 6, line 39 -column 8, line 14; figures 4,11-14 ---	1,10,11, 14,15, 20,22 6,16,18
X	WO 97 21072 A (SHERIKON INC) 12 June 1997 (1997-06-12) cited in the application page 8, line 24 - line 39 ---	1,11,14, 15,20,22
Y	EP 0 679 883 A (ELECTRONIC AUTOMATION LTD) 2 November 1995 (1995-11-02) column 4, line 3 -column 5, line 4; figures 2-5 --- -/--	6,16

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 October 1999	18/10/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Arca, G

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INTERNATIONAL SEARCH REPORT

Intr 'tonal Application No
PCT/IL 99/00364

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 753 905 A (RINGLIEN JAMES A) 19 May 1998 (1998-05-19) abstract	18

1

Form PCT/ISA/210 (continuation of second sheet) (July 1992)